5. ENVIRONMENTAL CONSEQUENCES OF LONG-TERM REPOSITORY PERFORMANCE

This chapter describes potential human health impacts from radioactive and nonradioactive materials released to the environment during the first 10,000 years after closure of a repository at Yucca Mountain. The impact calculations assumed that the population in the Yucca Mountain region would remain constant at the number of people projected to live in the region in 2035, as discussed in Chapter 3, Section 3.1.7.1. This chapter also estimates the peak radiation dose during the first 1 million years after closure. Closure of a repository would include the following events, which are analyzed in Chapter 4:

- Sealing of the underground emplacement drifts

- Backfilling and sealing of other underground openings

- Removal of the surface facilities

- Creation of institutional controls, including land records and surface monuments, to identify the location of the repository and discourage human intrusion

In addition, this chapter discusses estimates of potential biological impacts from radiological and chemical groundwater contamination and potential environmental impacts of such contamination and potential biological impacts from the long-term production of heat due to decay of the radioactive materials that would be disposed of in a repository at Yucca Mountain; and potential environmental justice impacts. Other than human impacts, these would be the only potential long-term impacts. There would be no repository activities; no changes in land use, employment of workers, water use or water quality other than from the transport of radionuclides; and no use of energy or other resources, or generation or handling of waste after closure of a repository. Therefore, analysis of impacts to land use, noise, socioeconomics, cultural resources, surface-water resources, aesthetics, utilities, or services after closure is not required. As part of closure activities, the U.S. Department of Energy (DOE, or the Department) would return the land to its original contour and erect appropriate monuments marking the repository, which would result in some minor impacts on aesthetics depending on the exact design of the monuments (currently undetermined). Impacts from closure are discussed in Chapter 4. After the completion of closure, risk of sabotage or intruder access would be highly unlikely. Chapter 4 (Section 4.1.8.3) discusses the potential for sabotage prior to closure. Section 5.7.1 discusses potential impacts from an intruder after closure.

DOE performed the analysis of potential impacts after repository closure for two operating modes—higher-temperature and lower-temperature. For analysis purposes, the same fundamental repository design was used in both modes, but the heat output per unit area of the repository was varied by changing waste package spacing and other operational parameters (see Section 2.1.1.2 in Chapter 2 for details).

The analysis for this EIS considered the following three transport pathways through which spent nuclear fuel, high-level radioactive waste, and hazardous or *carcinogenic* chemicals could reach human populations and cause health consequences:

- Groundwater
- Surface water
- Atmosphere

The principal *exposure pathway*, groundwater, would result from rainwater migrating down through the unsaturated zone into the repository, dissolving some of the material in the repository, and carrying contaminants from the dissolved material downward through the unsaturated zone and on through the groundwater system to locations where human exposure could occur. A surface-water pathway could occur if groundwater reached the surface at a discharge location, so the analysis for this Final EIS considered surface-water consequences along with groundwater consequences. An airborne pathway could result because spent nuclear fuel contains some radionuclides in gaseous form. For example, carbon-14 could migrate to the surface in the form of carbon dioxide gas and mix in the atmosphere.

The analysis for this EIS estimated potential human health impacts from the groundwater transport pathway at three locations in the Yucca Mountain groundwater hydrology region of influence:

- Water wells at the *reasonably maximally exposed individual* (RMEI) location [For this EIS, DOE determined that the RMEI location would be at the southern-most point of the controlled area, as specified in 40 CFR Part 197 (36 degrees, 40 minutes, 13.6661 seconds north latitude). Groundwater modeling indicates that the point at which the predominant groundwater flow crosses the boundary would be about 18 kilometers (11 miles) downgradient from the potential repository. This EIS refers to this location as the "RMEI location."]

- 30 kilometers (19 miles) downgradient from the potential repository.

- The nearest surface-water discharge point, which is about 60 kilometers (37 miles) downgradient from the potential repository.

These consequences are presented in terms of radiological dose and the probability of a resulting latent cancer fatality. A latent cancer fatality is a death resulting from cancer caused by exposure to ionizing radiation or other carcinogens.

DOE assessed the processes by which waste could be released from a repository at Yucca Mountain and transported to the environment. The analysis used computer programs developed to assess the release and movement of radionuclides and hazardous materials in the environment. Some of the programs analyzed the behavior of engineered components such as the waste package, while others analyzed natural processes such as the movement of groundwater. The programs are based on the best available geologic, topographic, and hydrologic data and current knowledge of the behavior of the materials proposed for the system. The analysis used data from the Yucca Mountain site characterization activities, material tests, and expert opinions as input parameters to estimate human health consequences. Many parameters used in the analysis cannot be exactly measured or known; only a range of values can be known. The analysis accounted for this type of uncertainty; thus, the results are ranges of potential health consequences.

WASTE PACKAGE

A *waste package* consists of the waste form and any containers (disposal container, barriers, and other canisters), spacing structure or baskets, shielding integral to the container, packing in the container, and other absorbent materials immediately surrounding an individual disposal container, placed inside the container, or attached to its outer surface. The waste package begins its existence when the outer lid welds are complete and accepted and the welded unit is ready for emplacement in the repository.

The analysis for this Final EIS considered human health impacts during the first 10,000 years after repository closure and the peak dose during the first 1 million years after repository closure. Estimates of potential human health impacts from the *nominal scenario* (undisturbed by volcanic activity or human intrusion) included the effects of such expected processes as corrosion of waste packages, dissolution of waste forms, flow through the saturated and unsaturated zone, seismic events, and changing climate. Additional analyses examined the effects of exploratory drilling, criticality, and volcanic events.

A number of changes have occurred since the issuance of the Draft EIS. Several changes have been made to the repository and waste package designs and many changes have been made to the models used to analyze long-term repository performance. Key design changes important to the long-term performance include changes to the waste package design, changes to how thermal loading of the repository is implemented, and addition of titanium drip shields over the waste packages. Chapter 2, Section 2.1.2; Chapter 4, Section 4.1; Section 5.2; and Appendix I, Section I.2, and the supporting documents referenced therein contain more details on the design changes. In addition, many improvements have been made to the analysis models. These improvements have enhanced the sensitivity of the models to more processes and effects and have refined treatment of uncertainties in some areas. Table 5-1 summarizes the changes. The changes identified in the column titled "S&ER Reference" were addressed in the Supplement to the Draft EIS. The other changes identified in Table 5-1 are addressed in this Final EIS. Further details can also be found in the references cited in Table 5-1 and in Appendix I, Section I.2. The relationship between published Total System Performance Assessment (TSPA) models and both the Draft EIS and this Final EIS are provided in Figure 5-1.

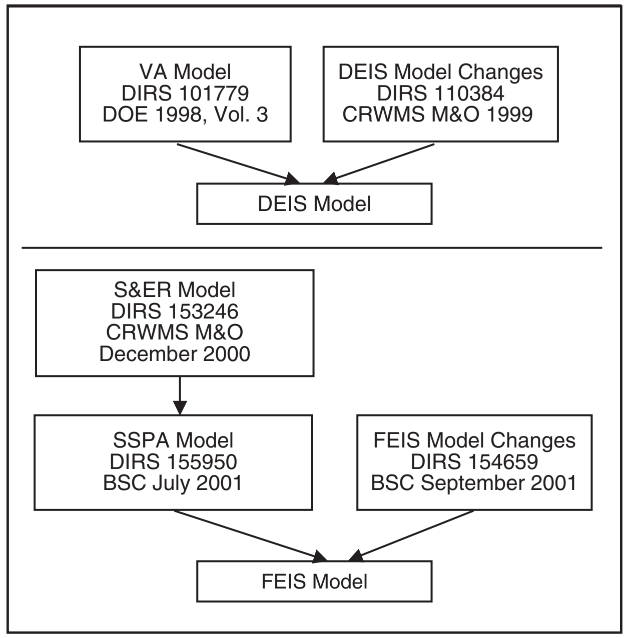

Figure 5-1. Relationship between the published TSPA models and models used for both the Draft EIS and this Final EIS.

5.1 Inventory for Performance Calculations

DOE proposes to dispose of approximately 11,000 to 17,000 waste packages containing as much as 70,000 MTHM of spent nuclear fuel and high-level radioactive waste in a repository at Yucca Mountain. There are several different types of disposal containers for commercial spent nuclear fuel and different container designs for DOE spent nuclear fuel and high-level radioactive waste. The exact number of waste packages would depend on various options in the proposed design. This long-term consequence analysis identified the inventory by the source category of waste material to be disposed of (commercial spent nuclear fuel, DOE spent nuclear fuel, weapons-usable plutonium, and high-level radioactive waste). For purposes of modeling, the inventory for each of the categories was averaged into an appropriate number of packages, each with identical contents. The average of the modeled inventories resulted in a total of nearly 12,000 idealized waste packages (slightly higher than the actual number of waste packages that would be emplaced) in two basic types.

Note that while the simulations were based on the nearly 12,000 packages, there would be no difference in the result if the smaller packages had been used (17,000 package case). This is because the use of smaller packages is merely a way of implementing the lower-temperature operating mode and would contain the same proposed inventory.

5.1.1 INVENTORY OF RADIOACTIVE MATERIALS

There are more than 200 radionuclides in the waste inventory (see Appendix A). The analysis for this Final EIS used a reduced number of radionuclides (26; see Appendix I, Section I.3).

Table 5-1. Changes to the TSPA model since publication of the Draft EIS (page 1 of 2).

Submodel	Change	Estimated effect	S&ER reference[a]	SSPA reference[b]	Model for this Final EIS[c]
Inventory	New inventory abstraction	Neutral	4.2.6.4.1		
	U.S. Navy spent nuclear fuel modeled as commercial spent nuclear fuel rather than as DOE-owned spent nuclear fuel	Neutral			5.2
Unsaturated zone flow	Updated climate model	Neutral	4.2.1.1.1		
	Added interaction of moisture in fractures and rock matrix	Possible reduction in dose	4.2.1.1.4		
	Added perched water models	Neutral	4.2.1.3.1.2		
	Flow through unsaturated zone and, therefore, seepage varies with time	More climate sensitivity, possible increase in dose	4.2.1.3.6		
	Flow-focusing within heterogeneous permeability field; episodic seepage	Possible increase in dose		4.3.1, 4.3.2, 4.3.5	
	Multiscale thermal-hydrologic model, including effects of rock dryout	Possible increase in dose		5.3.1	
	Thermal property sets	Neutral		5.3.1	
	Thermal effects on seepage	Possible increase in dose		4.3.5	
	Coupling between thermal, hydrologic, and chemical effects	Possible increase in dose	4.2.2.1.2		
Waste package and drip shield degradation	Changes to model new package design and addition of drip shield model	Decrease in dose up to 10,000 years	4.2.4.3		
	Improved early package failure model	Decrease in dose up to 10,000 years		7.3.2	
	Experimental corrosion data replacing expert judgment	Decrease in dose up to 10,000 years, increase in peak dose after 10,000 years	4.2.4.3.2		
	General corrosion rate independent of temperature	Increase in dose			5.2
Waste form degradation	Updated cladding degradation model to include mechanical failures and localized corrosion	Increase in dose	4.2.6.3.3		
	Add comprehensive model of colloid formation effects on radionuclide mobilization	Increase in dose	4.2.6.3.8		
	Increased number of radionuclides modeled from 9 to 21	Increase in dose	4.4.1.4		
	Neptunium solubility model incorporating secondary phases	Decrease in dose after 10,000 years	4.2.6.3.7		
Engineered barrier system transport	New comprehensive model for transport of radionuclides from colloid effects	Increase in dose	4.2.7.4.2		
Unsaturated zone transport	New comprehensive model for transport of radionuclides from colloid effects	Increase in dose	4.2.8.4.3		
	Model updated to include radiation connections in the thermal-hydrologic submodel for the lower-temperature operating mode	Neutral			5.2
	Effect of drift shadow zone-advection/ diffusion splitting	Decrease in dose		11.3.1	

Table 5-1. Changes to the TSPA model since publication of the Draft EIS (page 2 of 2).

Submodel	Change	Estimated effect	S&ER reference[a]	SSPA reference[b]	Model for this Final EIS[c]
Saturated zone flow and transport	Colloid-facilitated transport in two modes: as an irreversible attachment of radionuclides to colloids, originating from waste, and as an equilibrium attachment of radionuclides to colloids	Increase in dose	4.2.9.4		
	Three-dimensional transport model	Neutral	4.2.9.4		
	Plume capture method for well concentrations (total radionuclides dissolved in water usage)	Possible decrease in dose	4.2.9.4		
	Change in length of saturated zone from 20 kilometers (12 miles) downgradient from the potential repository for MEI[d] in Draft EIS to RMEI[e] location determined by DOE to be approximately 18 kilometers, or 11 miles, downgradient from the potential repository	Possible increase in dose			5.2
Biosphere	Change in basis for biosphere dose conversion factors from MEI in the Draft EIS to the average member of the critical group defined in draft 10 CFR Part 63	Neutral	4.2.10.1		
	Change in basis for biosphere dose conversion factors from the average member of the critical group (10 CFR Part 63) in the S&ER and SSPA to the RMEI defined in EPA regulation 40 CFR Part 197	Slight decrease			5.2
	Consideration of groundwater protection standards	New impact measure	4.4.2		
	Change in water volume used for evaluation of groundwater protection standards from sampled model dilution volume to the representative volume (3,000 acre-feet per year) defined in EPA regulation 40 CFR Part 197	Decrease in new impact measure			5.2

a. Section numbers in the *Yucca Mountain Science and Engineering Report: Technical Information Supporting Site Recommendation Consideration* (DIRS 153849-DOE 2001, all).
b. Section numbers in the SSPA-*Supplemental Science and Performance Analysis* (DIRS 155950-BSC 2001, all).
c. Section numbers in DIRS 157307-BSC (2001, Enclosure 1).
d. MEI = maximally exposed individual.
e. RMEI = reasonably maximally exposed individual.

The number of radionuclides to be analyzed was determined by a screening analysis. The screening analysis identified those radionuclides that would collectively contribute at least 95 percent of the dose to a person living in the vicinity of Yucca Mountain. The list of radionuclides resulting from the screening process forms the basis for the analyses discussed in this chapter. Appendix I, Section I.3, contains more details of this screening analysis.

The total inventory was abstracted into two types of idealized waste packages: a codisposal package with high-level radioactive waste in a glass matrix and DOE spent nuclear fuel, and a commercial spent nuclear fuel package. Table 5-2 lists the abstracted inventory for the idealized waste packages. For

IDEALIZED WASTE PACKAGES

The number of waste packages used in the performance assessment simulations do not exactly match the number of actual waste packages projected for the Proposed Action.

The TSPA model uses two types of *idealized waste packages* (commercial spent nuclear fuel package and codisposal package), representing the averaged inventory of all the actual waste packages used for a particular waste category.

While the number of idealized waste packages varies from the number of actual waste packages, the total radionuclide inventory represented by all of the idealized waste packages collectively is representative of the total inventory, for the radionuclides analyzed, given in Appendix A of this EIS for the purposes of analysis of long-term performance. The abstracted inventory is designed to be representative for purposes of analysis of long-term performance and cannot necessarily be used for any other analysis, nor can it be directly compared to any other abstracted inventory used for other analyses in this EIS.

Table 5-2. Abstracted inventory (grams) of radionuclides passing the screening analysis in each idealized waste package.[a,b]

Nuclide	Commercial spent nuclear fuel waste packages[c]	Codisposal waste packages[d]	
		DOE spent nuclear fuel	High-level radioactive waste
Actinium-227	0.00000309	0.000113	0.000467
Americium-241	10,900	117	65.7
Americium-243	1,290	1.49	0.399
Carbon-14	1.37	0.0496	0.00643
Cesium-137	5,340	112	451
Iodine-129	1,800	25.1	48
Neptunium-237	4,740	47.9	72.3
Protactinium-231	0.00987	0.325	0.796
Lead-210	0	0.000000014	0.000000114
Plutonium-238	1,510	6.33	93.3
Plutonium-239	43,800	2,300	3,890
Plutonium-240	20,900	489	381
Plutonium-242	5,410	11.1	7.77
Radium-226	0	0.00000187	0.0000167
Radium-228	0	0.00000698	0.00000319
Strontium-90	2,240	55.4	288
Technetium-99	7,680	115	729
Thorium-229	0	0.0266	0.00408
Thorium-230	0.184	0.0106	0.00782
Thorium-232	0	14,900	7,310
Uranium-232	0.0101	0.147	0.000823
Uranium-233	0.07	214	11.1
Uranium-234	1,830	57.2	47.2
Uranium-235	62,800	8,310	1,700
Uranium-236	39,200	853	39.8
Uranium-238	7,920,000	509,000	261,000

a. Source: DIRS 154841-BSC (2001, Table 36, p. 38).
b. The idealized waste packages in the simulation (model) are based on the inventory abstraction in Appendix I, Section I.3. While the total inventory is represented by the material in the idealized waste packages, the actual number of waste packages emplaced in the potential repository would be different.
c. There are 7,860 idealized commercial spent nuclear fuel waste packages.
d. There are 3,910 idealized codisposal waste packages.

analysis purposes, naval spent nuclear fuel is conservatively modeled as commercial spent nuclear fuel (DIRS 152059-BSC 2001, all; DIRS 153849-DOE 2001, Section 4.2.6.3.9, p. 4-257).

5.1.2 INVENTORY OF CHEMICALLY TOXIC MATERIAL

DOE is not proposing to dispose of chemically toxic waste in the potential repository. However, the degradation of engineered materials that would be used in repository construction and engineered barrier systems would result in corrosion products that contain chemically toxic materials.

A screening analysis reported in Appendix I (Section I.6.1) showed that the only chemical materials of concern for the 10,000-year analysis period were those released as the external wall of the waste package and the waste package support pallet materials corroded. The chemicals of concern would be chromium, nickel, molybdenum, and vanadium. The exposed surface areas that would corrode include Alloy-22 surfaces (drip shield rails, outer layer of waste packages, and portions of the emplacement pallets) and stainless steel 316NG surfaces (portions of the emplacement pallets).

The total quantities of materials would be 86,000,000 kilograms (190,000,000 pounds) of Alloy-22 (DIRS 150558-CRWMS M&O 2000, p. 6-6) containing 22.5 percent chromium, 14.5 percent molybdenum, 57.2 percent nickel, 0.35 percent vanadium (DIRS 104328-ASTM 1998, all) and 140,000,000 kilograms (310,000,000 pounds) of stainless steel, (DIRS 150558-CRWMS M&O 2000, p. 6-6) which is 17 percent chromium, 12 percent nickel and 2.5 percent molybdenum. A large percentage of the stainless steel would be inside the waste package (as an inner sleeve) and, therefore, much of this material would not be exposed until the Alloy-22 had corroded away.

5.2 System Overview

Radioactive materials in the repository would be placed at least 200 meters (660 feet) beneath the surface (DIRS 154554-BSC 2001, pp. 28-29). In physical form, the emplaced materials would be almost entirely in the form of solids with a very small fraction of the total radioactive inventory in the form of trapped gases (see Section 5.5). With the exception of a small amount of radioactive gas in the fuel rods, the primary means for the radioactive and chemically toxic materials to contact the *biosphere* would be along groundwater pathways. The materials could pose a threat to humans if the following sequence of events occurred:

- The waste packages and their contents were exposed to water
- Radionuclides or chemically toxic materials in the package materials or wastes became dissolved or mobilized in the water
- The radionuclides or chemically toxic materials were transported in water to an aquifer, and the water carrying radionuclides or chemically toxic materials was withdrawn from the aquifer through a well or at a surface-water discharge point and used directly by humans for drinking or in the human food chain (such as through irrigation or watering livestock).

Thus, the access to, and flow of, contaminated water are the most important considerations in determining potential health hazards.